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High quality investment castings have been increasingly selected for use on commercial and military aircraft due to their cost and weight benefits. Thin wall titanium and aluminum cast components have replaced many heavy complicate and manufacturing intensive, multipiece parts. Thick investment cast parts weighing up to 400 lb have become a reality. Also, welded titanium castings are being implemented on newly developed military aircraft. However, several issues critical for the wide implementation of this casting technology have yet to be adequately addressed: inspection of thick sections, effect of defects (porosity, shell inclusions, especially the halo zone) on the fatigue performance, heat treatment, lack of specifications, and applications of the casting factor. Another major casting implementation issue pertinent to our aging aircraft systems is the requirement for qualification testing. There are no clear guidelines as to whether or not costly and lengthy qualification tests are required for the substitution for every part. This paper will discuss these issues and the efforts to overcome the problems.

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Cast Development for Aging Aircraft

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ABSTRACT

High quality investment castings have been increasingly selected for use on commercial and military aircraft due to their cost and weight benefits. Thin wall titanium and aluminum cast components have replaced many heavy complicate and manufacturing intensive, multi-piece parts. Thick investment cast parts weighing up to 400 pounds have become a reality. Also, welded titanium castings are being implemented on newly developed military aircraft. However, several issues critical for the wide implementation of this casting technology have yet to be adequately addressed: inspection of thick sections, effect of defects (porosity, shell inclusions, especially the halo zone) on the fatigue performance, heat treatment, lack of specifications, and applications of the casting factor. Another major casting implementation issue pertinent to our aging aircraft systems is the requirement for qualification testing. There are no clear guidelines as to whether or not costly and lengthy qualification tests are required for the substitution for every part. This paper will discuss these issues and the efforts to overcome the problems.

INTRODUCTION

In an environment of defense budget cutting, the NAVAIR (Naval Air Systems Command) Team is engaged in the areas of improvement, such as affordable readiness and reducing cost of products. Affordable readiness will become increasingly important as the Navy's aircraft continue to age. In response to this situation, casting technology will play a big role in reducing cost of aircraft and meet affordable readiness requirements by consolidating sub-components and replacing some aging parts of airframe structures.

High quality investment castings have been increasingly selected for use on commercial and military aircraft due to their cost and weight saving benefits. Efforts have been made to consolidate very complicate and manufacturing intensive multi-piece parts in secondary structures. Part counts, joint materials, labor and weight are significantly reduced as an integral component. For example, a one-piece transmission adapter made from investment cast titanium which has been successfully implemented on V-22 Osprey. The cast transmission adapter is originally fabricated by joining eight parts and 395 fasteners, and the cost is reduced by $50K. Many thin-wall titanium and aluminum cast components have been implemented in Navy aircraft. Thick investment cast parts weighing up to 400 pounds have become a reality due to the high quality casting process. Also, welded titanium castings are being implemented on newly developed military aircraft to replace either mechanical or adhesive jointing.

However, there are several issues critical for the wide implementation of this casting technology: (a) NDI criteria for thick sections and shell mold inclusion, (b)the effect of defects (porosity, shell inclusions, especially the halo zone) on the fatigue performance, (c)heat treatment, (d)the lack of specifications and (e)the applications of the casting factor. Another major casting implementation issue for substitution in aging systems is a requirement for qualification testing. There are no clear guidelines as to whether or not the lengthy qualification tests are required for the substitution for every part. The Navy has been active in the development and implementation of aerospace structural castings. The Navy has formed a casting working group and is involved in the RDT&E of fabricating thick-section structure, welding joining and the characterizing HIP effect on static and dynamic properties. Due to the lack of specifications for designers to use, a government/industry steering group in conjunction with MIL HDBK-5 committee was formed. Out of the group, Howmet and PCC have agreed cast 10 heats of 2" ~ 5" thick Titanium as a part of round robin test program to generate MIL HDBK-5 data. This will significantly boost the confidence in using thick titanium castings.

Casting factor has traditionally been used to offset inconsistencies in mechanical properties. If designing components without a casting factor, cost and weight can be significantly reduced. Recent advances in process control at investment cast foundries reduce the variability of mechanical properties of cast structures, as illustrated in Figure 1. It now creates the opportunity to produce low cost, weight saving castings to replace higher cast, critical Navy aircraft parts. F/A-18 projects have conducted a program to verify process control capability at foundry facilities to demonstrate the possibility of designing F/A-18E/F components with a casting factor of 1.0, or without a casting factor.

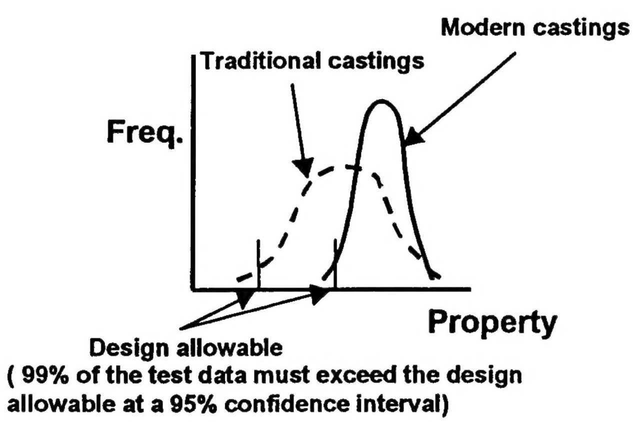


Figure 1. Scattering data of cast materials

The ONR 6.2 and ManTech Affordable Casting Technology initiatives have been established for affordable and reliable titanium and aluminum castings. The project studies void healing by HIP (hot isostatic press) in Ti and aluminum castings, and sets up a round robin program for Ti casting with different heat treatments to establish data base for design. The results are critical for the general Ti community to clarify the problems associated with large structural Ti cast airframe components.

Casting aluminum alloys are widely used in the aircraft industry because they offer reduction in part weight, process flow time, and better dimensional fit and control. They also enable near net-shape manufacturing of aerospace structural components of high complexity, which reduces the parts consolidation, and in turn cut down manufacturing cost. Current airframe structures made from aluminum include emergency exit door, pressurized access doors, electronics access door, flirt-pods, intermediate wing, lex vent flap, nacelle components, etc. Engine structures, such as gear boxes, front frames and structural intake ducts are also made aluminum.

Despite that aluminum castings are in a more mature state than are titanium castings, they are not widely used in Navy aircraft. For instance, aluminum castings are not used for primary structure in the F-18E/F. There are aluminum investment castings used for access door in C-17 aircraft. The main aluminum casting material is D357-T6 alloy. The hesitation to use aluminum castings may be that the designers have a lack of experience with castings and have misconceptions and ignorance about castings. Other issues are the long lead times to get casting products, available data base to access, and small number of suppliers. However, with the potential to greatly reduce the costs to the DoD by designing more aluminum castings in aircraft, the future activities for the F-18E/F may include structural doors, control surface assemblies, some subsystems.

As previously mentioned, airframe manufacturers have reluctance to use castings because of the variability of mechanical properties and quality. One of the factors which governs the quality of the cast aluminum is porosity formed during the casting process as a result of alloy shrinkage and gas evolution during solidification. Although today's premium quality castings are manufactured and inspected using much more controlled process, porosity formation is still possible. Porosity degrades properties especially on fatigue resistance, damage tolerance. Therefore, fatigue-critical cast parts need to be densified in order to heal voids in the material.

Hot isostatic press (HIP) is the only process which so far provided most effectiveness in healing voids from a wide range of materials. HIP is a process which uses high temperatures in combination with high isostatic pressures to heal porosity. During HIP, densification occurs because of the elimination of some porosities. Work(1) has shown that some micro-porosities can be eliminated by working and heat treatment, however, even after extensive working and heat treatment, small amounts of micro-porosity still exist. HIP offers some promises in manufacturing procedures because components show significant properties improved by the HIP process. The HIPed materials have shown less variability in strength.(2) Although work on HIP has been performed mostly on powder compacts, little study has been done on castings. Specifically, it has not been fully established if all forms of porosity present in castings can be eliminated by HIP and consequently improve mechanical properties, especially on their fatigue properties.

Although D357 is widely used for aluminum castings in Navy aircraft, A356 is chosen among the premium-quality sand and permanent mold casting alloys specified for military and aircraft applications. Alloy A356 is in the group of aluminum-silicon alloys which have excellent casting characteristics, weldability, pressure tightness, and corrosion resistance. These alloys are heat treatable to provide various combinations of tensile and physical properties. The effects of these microstructural parameters on tensile properties have been extensively

studied.(3,4) However, only recently, the role of fracture, fatigue, and impact property data in optimizing design parameters has become important to the designers of A356 castings, and several studies have been initiated.(5,6) In this paper, the effect of HIPing on the porosity healing and fatigue properties is discussed.

Experimental Study

Half of the A356 specimens were cast in premium condition (cast condition I), and the rest were cast in higher temperature (cast condition II), which results in higher porosity content. A356 specimens were produced and tested in (i) the as-cast, (ii) the HIPed, and (iii) the Densal HIPed conditions in order to achieve an understanding on the effect of HIPing on microstructure and mechanical properties. HIPed specimens were processed at a pressure of 103MPa (15 Ksi) and a temperature of 516 °C (960°F) for two hours. Densal is a company proprietary HIP process which employs reduced temperature, pressure and hold time as compared to the premium HIP process for cast aluminum.

The microstructure and volume fraction porosity for each type of processing condition will be assessed. The main objective was to determine what degree HIP closes the voids in the material and to assess whether low cost Densal HIP can achieve the same results as premium HIP. For each group of specimens, static tensile and high cycle fatigue tests will be conducted to relate the tensile properties, such as yield stress and strength, and fatigue S-N curves with the casting conditions and HIPing. But, only the effect of HIPing on the porosity healing and fatigue properties of the unHIPed, HIPed and Densal HIPed cast A356 specimens will be presented.

The effect of HIP on porosity

The porosity content was quantified for the specimens in the as-cast, HIPed, and the HIPed + T6 conditions. Each type of specimen was cut in order to provide two internal sections for polishing and examined under optical microscope. Twenty-five different fields from each section were interrogated using an image analyzer. The size distribution and measurement of volume fraction of porosity for each field were documented. The representative structures of the as-cast, HIPed+T6, and Densal HIPed+T6 specimens, respectively were presented in (7). The results show that the size of the porosities is greatly reduced after HIPing.

Figure 2 shows the HIPing effect on the porosity content of the specimens under premium HIP in both casting conditions. In the casting condition I, the porosity content is reduced about 50% for HIPed specimens, compared with as-cast specimens. While in casting condition II, the porosity content is reduced over 85% after HIP.

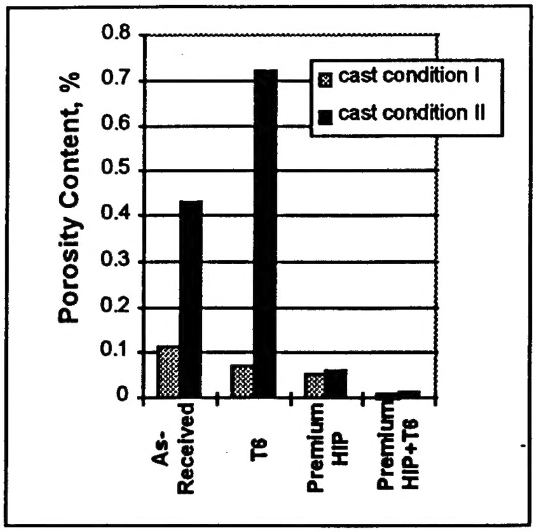


Figure 2. The effect of premium HIP on porosity content.

Because most A356 castings are used in the T6 condition, it is important to know the effect of T6 on the HIPed castings. From observation, the solution treatment and aging did not open the closed porosities, and instead, T6 helps further eliminate the pores. Figure 3 shows the HIPing effect on the porosity content of the specimens under Densal HIP. In the casting condition I, the porosity content is reduced about 20% for HIPed specimens, compared with as-cast specimens. While in casting condition II, the porosity content is reduced over 60% after Densal HIP.

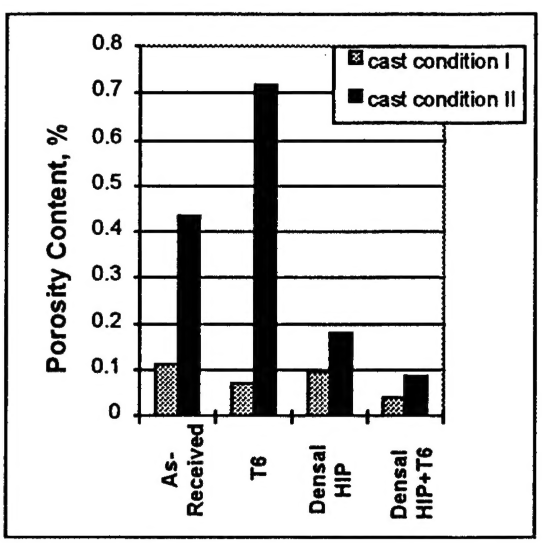
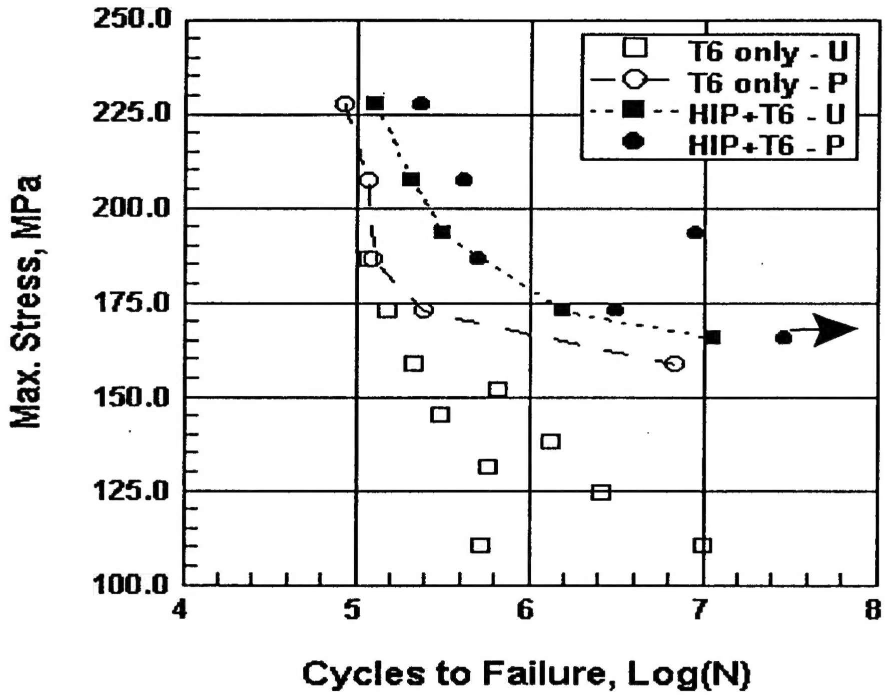


Figure 3. The effect of Densal HIP on porosity content.

In summary, specimens whether in premium casting condition(casting condition I) or in higher temperature casting condition(casting condition II), the porosity content is reduced to less than 0.015% after premium HIP and T6 processes. The premium HIP closes more porosities than the low cost Densal HIP does because higher temperature and pressure in the premium process allow larger plastic deformation, which is the main mechanism of pore closure.

Fatigue Properties

Fatigue crack initiation is very sensitive to the porosity content of a casting. HIPing helps to close the voids present in the casting, and in this way enhances their fatigue properties.



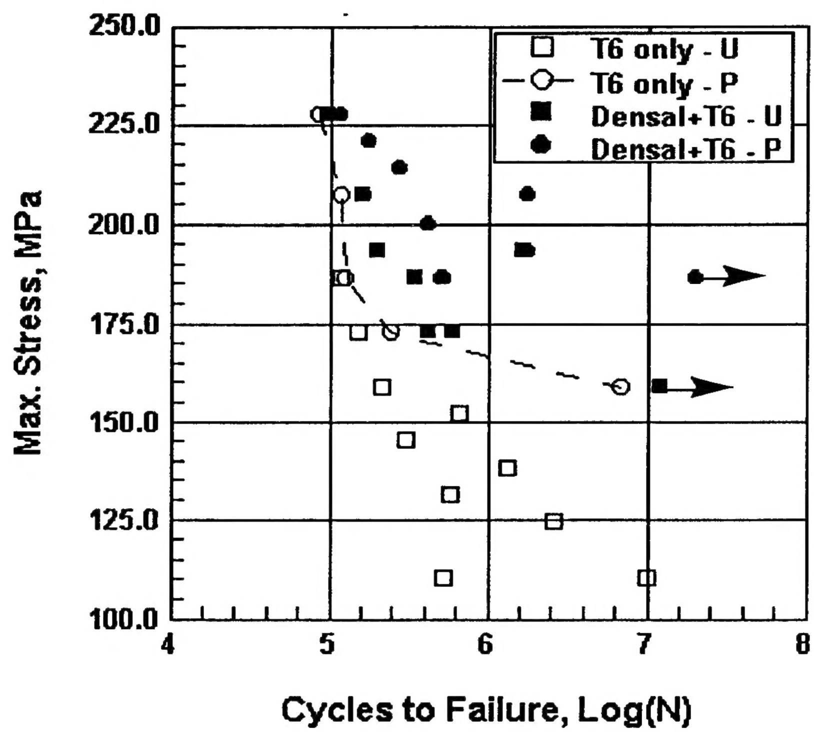
Note: U: low quality cast
P: premium quality cast

Figure 4. The Effect of Premium HIP on Fatigue Property

Figure 4 and Figure 5 show the preliminary S-N results for the specimens in their peak aged condition. Evidently, the premium HIP improves the fatigue life of cast A356 regardless of the casting conditions. Most premium HIPed specimens exhibit similar fatigue limit, 165 MPa, while specimens in higher temperature cast condition have only 110 MPa. Comparing the

fatigue life of material under premium cast condition, the HIPed specimens show about 14 MPa higher than the specimens without HIP. Regarding the cycles-to-failure, the premium cast specimens have 3 to 4 times longer life than the higher temperature cast specimens at lower fatigue stress (172 MPa). The HIPed premium cast specimens exhibit more than a decade longer life than the unHIPed premium cast specimens at 172 MPa fatigue stress, while about seven times longer life at 206 MPa fatigue stress.

Another observation shows that even in higher temperature casting condition, the specimens after either premium HIP (HIP+T6-U) or Densal HIP (Densal+T6-U) exhibit better fatigue life than unHIPed specimens in premium casting condition. In general, the premium HIPed specimens have better fatigue life, and premium cast specimens show better fatigue life.



Note: U: low quality cast
P: premium quality cast

Figure 5. The Effect of Densal HIP on Fatigue Property

Summary

Experimental results indicate that HIPing helps to close voids in cast aluminum. In general, the HIPed specimens show better fatigue life. Even in higher temperature casting condition, the specimens after either premium HIP or Densal HIP exhibit better fatigue life than the unHIPed

specimens in premium casting condition. The on-going work will be conducted on the optimum conditions of HIP to obtain the desired fatigue property with acceptable degree of porosity content.

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